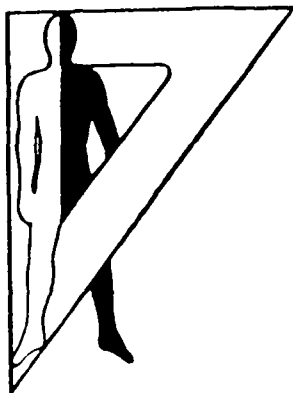④

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HAZARD FROM AN INTENSE MIDRANGE IMPULSE

G. Richard Price
Samuel Wansack

January 1990
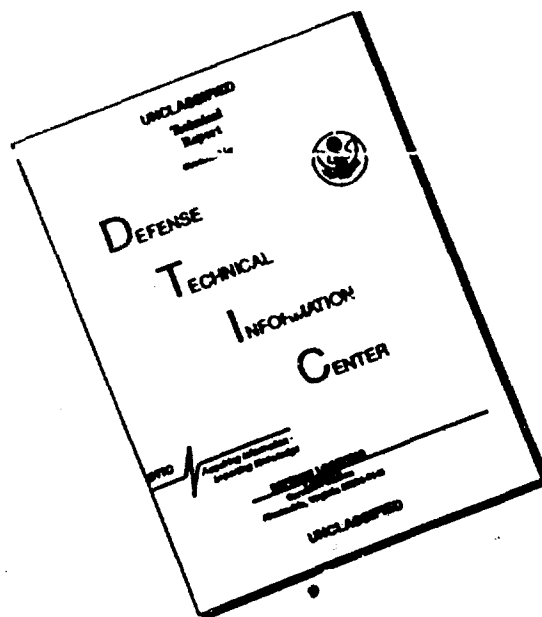AMCMS Code 611102.74A0011

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19 ABSTRACT *(Continue on reverse if necessary and identify by block number)*

It has been hypothesized that the ear would become increasingly susceptible to impulses (gunfire) as the spectral peak of the impulse approached the frequency region where the ear was tuned best (about 4 kHz for the cat ear) [G. R. Price, J. Acoust. Soc. Am. Suppl. 1 **62**, S95 (1977)]. This prediction was counter to the predictions of the world's damage-risk criteria for impulse noise. It has been supported by experiments using exposures to 100-Hz and 800- to 1000-Hz impulses; but no test had been run at the point of predicted maximum susceptibility. In the present experiment, three groups of cats were exposed to 50 impulses produced by a primer explosion (spectral peak at 4 kHz) at peak levels of 135, 140, or 145 dB.

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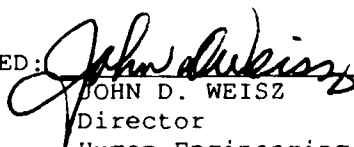
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Auditory thresholds were electrophysiologically measured from the vertex to 2-, 4-, 8-, and 16-kHz tone pips and losses were determined 30 min after exposure and more than 2 months post-exposure. Losses were greatest at 4 kHz, began to develop at 134-dB peak pressure, and the immediate losses grew at a rate of about 7 dB for every dB increase in peak pressure. About half of the loss measured immediately became permanent. The energy required to begin producing a permanent threshold shift was only about 0.07 J/m^2, far lower than that required with continuous noises at lower sound pressures. The data were interpreted as supporting the original hypothesis of greater susceptibility in the midrange.

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January 1990

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U.S. ARMY HUMAN ENGINEERING LABORATORY
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Hazard from an intense midrange impulse

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It has been hypothesized that the ear would become increasingly susceptible to impulses (gunfire) as the spectral peak of the impulse approached the frequency region where the ear was tuned best (about 4 kHz for the cat ear) [G. R. Price, J. Acoust. Soc. Am. Suppl. 1 **62**, S95 (1977)]. This prediction was counter to the predictions of the world's damage-risk criteria for impulse noise. It has been supported by experiments using exposures to 100-Hz and 800- to 1000-Hz impulses; but no test had been run at the point of predicted maximum susceptibility. In the present experiment, three groups of cats were exposed to 50 impulses produced by a primer explosion (spectral peak at 4 kHz) at peak levels of 135, 140, or 145 dB. Auditory thresholds were electrophysiologically measured from the vertex to 2-, 4-, 8-, and 16-kHz tone pips and losses were determined 30 min after exposure and more than 2 months post-exposure. Losses were greatest at 4 kHz, began to develop at 134-dB peak pressure, and the immediate losses grew at a rate of about 7 dB for every dB increase in peak pressure. About half of the loss measured immediately became permanent. The energy required to begin producing a permanent threshold shift was only about 0.07 J/m², far lower than that required with continuous noises at lower sound pressures. The data were interpreted as supporting the original hypothesis of greater susceptibility in the midrange.

PACS numbers: 43.63.Rf, 43.50.Pn, 43.50.Ba, 43.66.Gf

INTRODUCTION

About a decade ago, a research hypothesis was advanced that the ear would be differentially susceptible to intense acoustic impulses (gunfire), depending upon the location of the energy's spectral peak (Price, 1977). Specifically, the cat ear was predicted to be most susceptible to intense gunfire-like impulses in the 4-kHz region and less susceptible at both lower and higher frequencies. The decrease in susceptibility was projected to be about 3 dB/oct for the lower frequency impulses and about 12 dB/oct for the higher frequencies. In the intervening years, experiments in which cat ears were exposed to rifle or howitzer impulses have supported this contention on the low-frequency side (Price, 1986a,b; 1983); but no test had been run at the point of predicted maximum susceptibility.

The prediction of lower susceptibility to low-frequency impulses is at odds with the predictions of hazard by any of the world's damage-risk criteria for impulse noise [CHABA, 1968; Liang *et al.*, 1983; MIL STD-1474(B), 1979; Ministry of Defense, 1982a,b; Pfander, 1975; Smoorenberg, 1980]. Disagreements between this prediction and the traditional criteria vary with the criterion and the impulse; but, in general, the peak levels predicted to be hazardous by the criteria can disagree by 15 or 20 dB (Price, 1986a). Consequently, there is considerable practical interest in establishing the ear's true susceptibility so that hazard can be rated accurately, hearing can be protected adequately, and weapon design can perhaps be modified to accommodate the true susceptibility of the ear (Price, 1987).

The present experiments were therefore undertaken to further develop knowledge of the ear's susceptibility to a gunfire-like impulse that had its spectral peak near 4 kHz.

I. METHOD

A. Subjects

Subjects were 24 young female cats, weighing 2.5 kg on the average.[1] Both ears were used.

B. Impulse exposure

The impulse exposures were conducted inside an anechoic chamber. In addition to providing somewhat better acoustic control than live firing outdoors, this procedure also eliminated the ground reflection that is normally present for gunfire exposures. In order for a Friedlander-like waveform to have its peak energy at 4 kHz, the duration of its initial positive peak (*A* duration) should be about 70 μs. An impulse source was constructed to allow the firing of small rifle primers down a barrel (7-mm bore) extending into the chamber.

The brevity of the impulse made an accurate assessment of the details of the waveform difficult; therefore, some explanation of the procedures used may be helpful. If the recording is done with the microphone diaphragm normal to the wave front, then the wave is reflected from the diaphragm and the peak pressure recorded is typically double that recorded with grazing incidence. On the other hand, if the wave front meets the diaphragm at grazing incidence, the travel time across a 1/4-in. diaphragm is on the order of 20 μs. This has the effect of extending the measured rise time of the impulse, so that the true peak pressure is underestimated (transit-time error or gauge-size error). This is not a significant error for impulses that have relatively long durations (and for small diameter microphones); however, for an impulse of the length used here, the error in estimation of peak

pressure could be on the order of 2 dB. This problem has been discussed by Baker (1973) who suggests that the true pressure be estimated by measuring at a grazing angle of incidence and extrapolating the decaying pressure backwards as shown in Fig. 1. A mathematically more rigorous modeling of the passage of a shock front across a sensitive surface on a blunt cylinder (Van Houten and Brown, 1968) yields essentially the same result. The values used for peak pressure in this article were derived by such an extrapolation. The pressures were recorded with a 1/4-in. Bruel and Kjaer Model 4136 condenser microphone with the grid cap removed and with the microphone diaphragm at grazing incidence to the wave front.

The animals were positioned facing the end of the barrel and at a distance and azimuth that produced the desired peak pressures and duration. The peak pressure had a standard deviation of 1 dB. An exposure consisted of 50 impulses presented at approximately 3-s intervals.

C. Determination of auditory sensitivity

Auditory sensitivity was determined by electrophysiological measures. Animals were injected with atropine and lightly anesthetized with intraperitoneal injections of sodium pentobarbital. They were placed in a sound attenuating room, head position was maintained by a head holder and they rested on a heating pad, which was cycled by a controller set to maintain rectal temperature at 38.6 °C. Sounds were delivered to the ear by a closed-tube sound system that allowed essentially independent testing of the two ears. The sound cannula contained a concentric probe for a condenser microphone and was securely taped into the external ear. Each frequency was calibrated for each ear, each day.

Brain-stem potentials were picked up by surface electrodes over the vertex and frontal sinus with the head holder serving as ground. They were amplified, filtered, and signal averaged on a Nicolet MED-80 computer. The brain-stem response, commonly designated wave V, was followed to establish sensitivity. Standard stimuli were tone-pips shaped so there were three cycles of the tone on the rising, plateau, and falling portions and were presented with rolling phase at a 55-ms interstimulus interval. Stimulus intensity was varied in 5-dB steps and between 256 and 1024 responses were averaged, depending upon the response. Threshold was arbitrarily established as being 2.5 dB below the lowest SPL at which wave V could be identified. Four frequencies were tested: 2, 4, 8, and 16 kHz.

The highest SPL used in a test was limited to 90 dB in order to avoid the possibility that the test tones themselves would become hazardous if an ear were unresponsive. This limit had the secondary effect of restricting the maximum threshold shift measurable to 90 dB minus the preexposure threshold. For the purposes of data analysis, any time no response could be elicited at the highest SPL, a threshold shift of 80 dB was recorded.

D. Test procedure

On the day of exposure, the animal was lightly anesthetized and auditory thresholds were determined for the four

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GE: TAKEN AS TRUE PEAK PRESSURE
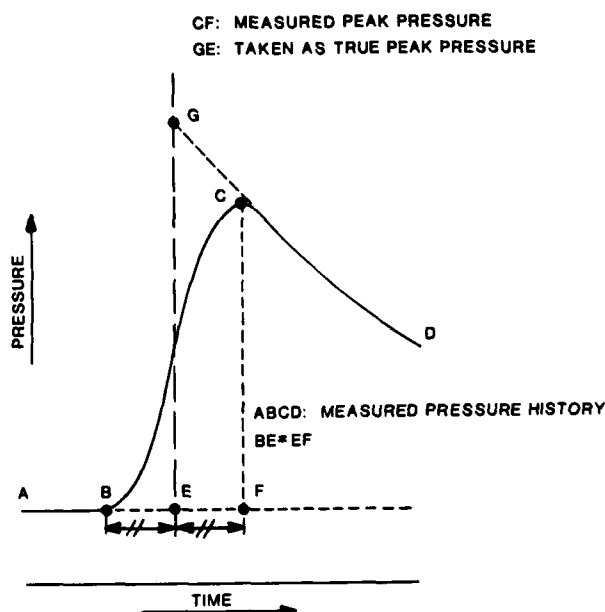
ABCD: MEASURED PRESSURE HISTORY
BE≈EF

TIME

FIG. 1. Method of extrapolation of pressure history to estimate the true peak pressure.

test frequencies. The anesthetized animal was then moved from the test chamber to the predetermined position in the anechoic chamber and exposed to 50 impulses. During exposure, it was facing the impulse source and its head position was maintained by a head holder that was entirely free of the ear and not between the ear and noise source. Following exposure, the animal was moved to the test chamber and its sensitivity was redetermined. The interval between exposure and beginning of the test was about 30 min. The animal's rectal temperature was monitored during exposure as well and was maintained at 38.6 °C by a second hot water heating pad and controller.

II. RESULTS AND DISCUSSION

A. The acoustic impulse

The pressure history of the 145-dB impulse is presented in Fig. 2, and the spectral analysis of the impulse in Fig. 3 shows that the spectral peak of the impulse was at 4 kHz. For the purpose of comparison with exposures to weapons impulses in previous experiments, the energy present in the impulse was computed with and without A-weighting, assuming that the peak pressure had been 154 dB (1.0 kPa). Had a primer impulse been at that pressure, the energy in it would have been 0.1 J/m². Because of the high-frequency content of the impulse, A-weighting would not affect it appreciably. By way of comparison at the same peak pressure, a rifle impulse would contain about 0.3 J/m² and a 105-mm howitzer impulse would contain about 2.6 J/m². The A-weighting would have changed these values to 0.25 and 0.8 J/m², respectively.
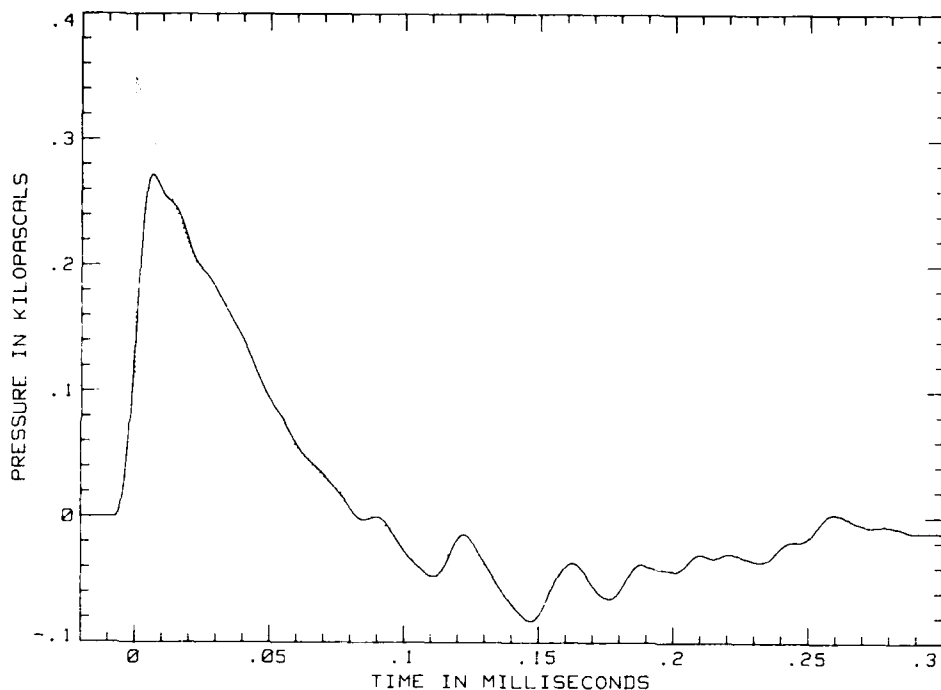
FIG. 2. Pressure history of the 145-dB impulse. The dotted line is the Friedlander waveform matching the pressure history.

B. Threshold shifts

1. Initial sensitivity

The mean initial sensitivity of all the ears to the four test frequencies is plotted in Fig 4. The shaded area in the figure is the area one standard deviation above and below the mean for data similarly derived from 115 ears used in previous experiments in this laboratory. The animals used in the present study had initial sensitivity measures that were essentially the same as previous animals.

2. Compound threshold shifts

The threshold shift measured immediately after an exposure may contain both temporary and permanent components; therefore, it is referred to as a compound threshold shift (CTS). Mean CTSs at the four test frequencies are plotted in Fig. 5 for the three exposure levels. Losses were seen at all the test frequencies, with the maximum shift at 4 kHz. The data for the 145-dB exposure contained many threshold shifts that were unmeasurably large; therefore, the CTS data
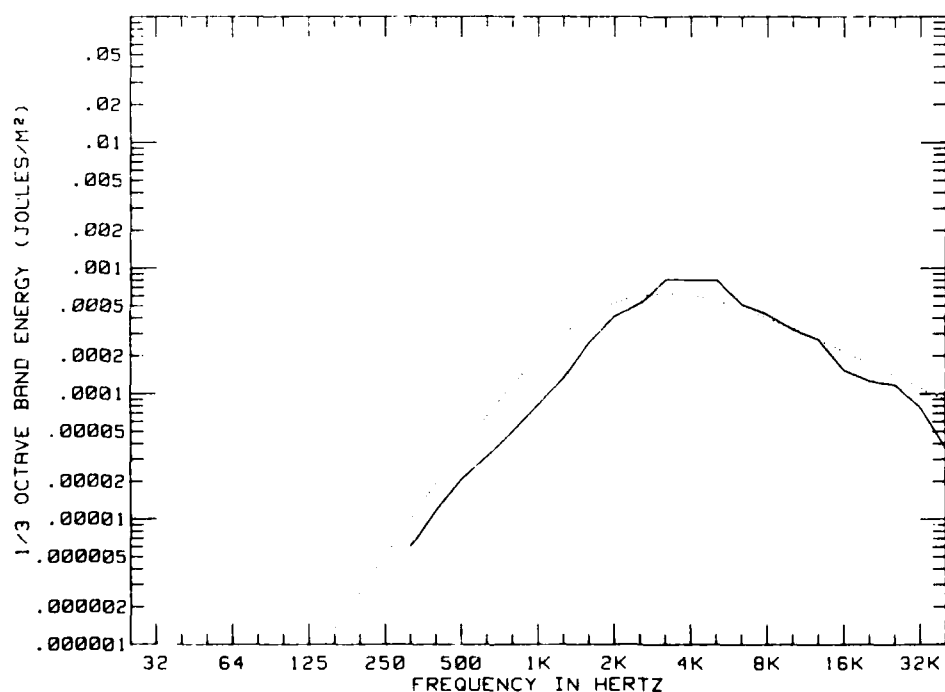

FIG. 3. Spectrum of the 145-dB impulse. The dotted line is the spectrum of the *Friedlander waveform fitting the impulse.*
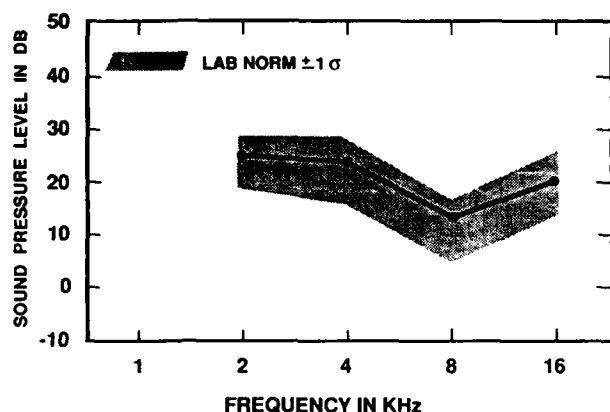
FIG. 4. Mean preexposure sensitivity of all the ears ($N = 52$). The shaded area covers the mean and ± 1 standard deviation for 115 ears in previous experiments.

FIG. 6. Mean permanent threshold shifts measured for the three experimental groups, measured 2 months or more after exposure.

(especially at 4 kHz) may, to some degree, reflect the convention of assigning an 80-dB shift when no response could be elicited.

3. Permanent threshold shifts

The mean permanent threshold shifts (PTSs) for the group at each of the exposure levels are portrayed in Fig. 6. The peak of loss remained at 4 kHz while about 1/2 of the CTS recovered for the 140- and 145-dB exposures. Recovery was essentially complete for the 135-dB condition. The question of whether or not a threshold shift will fully recover is critical, especially where the use of human subjects is contemplated.
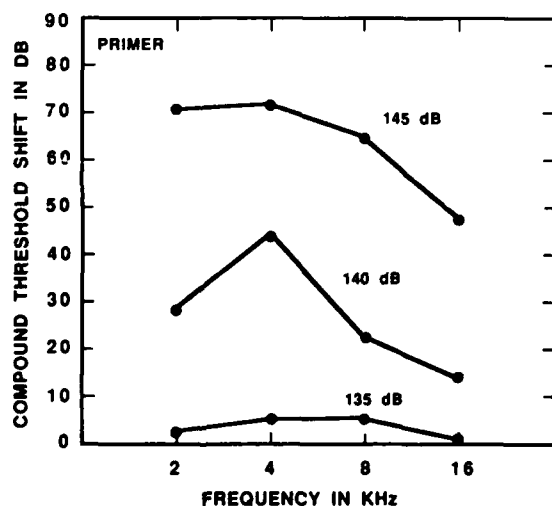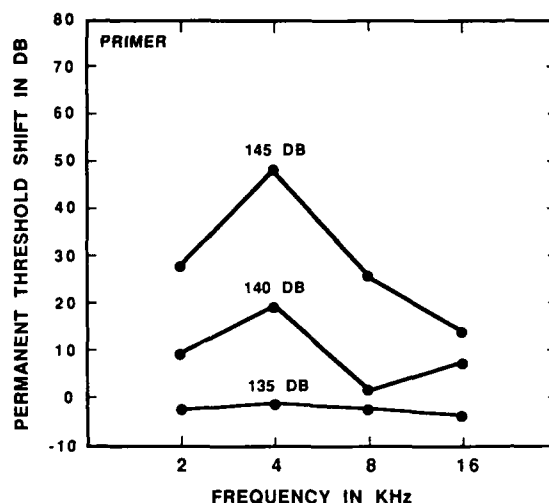
C. CTS/PTS relationship

The relationship between the CTS and the PTS from the present study is displayed in Fig. 7 for the 4-kHz test frequency (the area of greatest loss), with each data point representing one ear. The least-squares regression line is also plotted with the data. Three aspects are interesting. The slope of the line is 0.68 (dB PTS for each dB CTS), it intercepts the x axis at about 7.1 dB and the correlation coefficient is 0.81. Almost identical plots have been produced when the cat ear was exposed to the rifle and the howitzer

FIG. 7. Permanent threshold shift (PTS) at 4 kHz for individual ears plotted as a function of compound threshold shift (CTS) at the same frequency. The solid line is the least-squares fit to the data ($r = 0.81$, slope $= 0.68$, x intercept $= 7.0$). The dashed line marks equal CTS and PTS, indicating recovery below the line and additional loss above the line.

FIG. 5. Mean compound threshold shifts measured immediately after exposure for the three experimental groups.
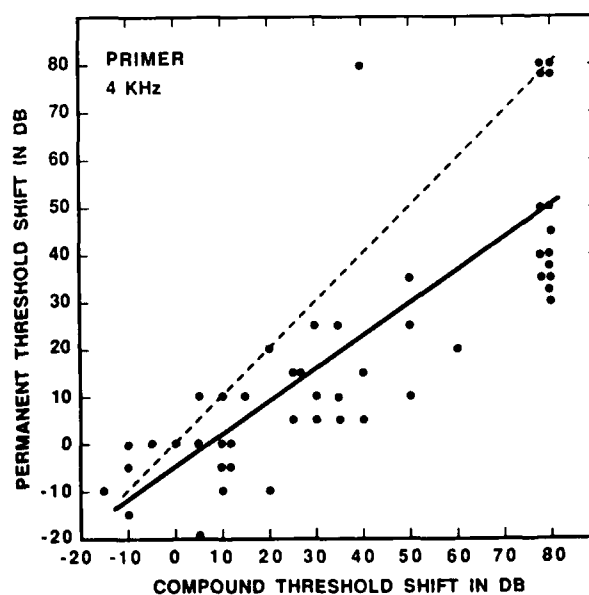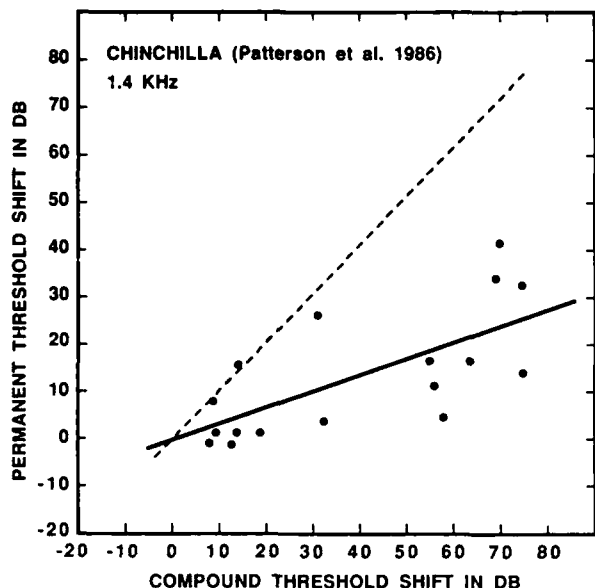
FIG. 8. Permanent threshold shift (PTS) at 1.4 kHz for individual chinchilla ears plotted as a function of compound threshold shift (CTS) at the same frequency. These data were taken from the report by Patterson *et al.* (1986). Exposure was to 100 sinusoidal impulses at 131-, 135-, or 139-dB peak pressure with a spectral peak at approximately 1.4 kHz. The solid line is the least-squares fit to the data ($r = 0.69$, slope $= 0.35$, x intercept $= 2.1$). The dashed line marks equal CTS and PTS, indicating recovery below the line and additional loss above the line.

old shifts determined at various times post-exposure; but, for comparison, the shifts measured at 1.4-kHz, 1-h post-exposure have been extracted from the report and in Fig. 8 have been plotted along with the PTSs. The correlation coefficient was a little less ($r = 0.69$), the slope was a little lower (0.35 dB of PTS per dB of CTS), and the intercept on the abscissa (2.1 dB) was also near zero CTS. The similarity in the data between the two species could be a function of a common damage/repair process in mammalian ears. The fact that the x-axis intercept is close to 0 dB for both species suggests that, for exposure to intense impulses, no threshold shift measurable 1/2 h or more after exposure to an intense impulse can be considered safe.

D. Growth of loss with intensity

In order to examine the rate at which CTS grows as intensity rises, CTSs at 4 kHz for all three exposure intensities are plotted in Fig. 9 along with the least-squares regression line fitting the data. The variability of the losses, although sizable, is still smaller than in previous studies with live firing of rifles and howitzers (Price, 1986b; 1983). This is reflected in the correlation coefficient of 0.91 for this study, which is in contrast with the corresponding coefficients of about 0.4 for the studies using weapons impulses. The reduced variability is perhaps not surprising given the more complete control of exposure conditions in the present experiment.

E. Hazard as a function of spectrum

The final point worth noting with respect to Fig. 9 is the pressure at which losses begin to grow. The regression line reaches zero loss at 134 dB. The equivalent calculation for rifle or howitzer impulses gives pressures of 139 and 144 dB, respectively (Price, 1986a). The ear appears to become progressively less susceptible to impulses as their spectral peaks depart from the midrange. Data consonant with this point are also available from the guinea pig ear. Dancer *et al.*

(Price, 1986a). For the cat ear, this finding is consistent for intense impulses, regardless of the location of the spectral peak in the impulse.

Parallel data that follow the same pattern are now available from another species. Patterson *et al.* (1986) exposed the chinchilla to 100 sinusoidal impulses from a speaker (spectral peak at about 1 kHz) at 131-, 135-, and 139-dB peak pressure. The data were behaviorally measured thresh-
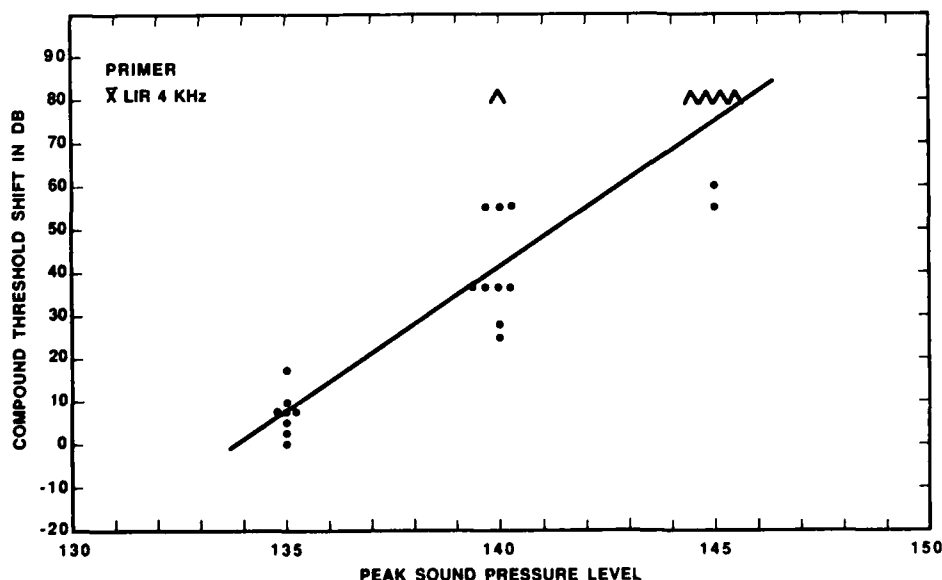

FIG. 9. Mean compound threshold shift in dB for left and right ears of each animal as a function of peak sound-pressure level for 50 primer impulses. The solid line is the least-squares line fitting the data ($r = 0.91$, slope $= 7.0$, x intercept $= 134$ dB).

(1985) used explosive devices to produce impulses with differing spectral peaks and they found that in spite of the fact that the lower frequency impulses had much more energy in them (for any given peak pressure), the guinea pig was most susceptible to the impulse with its spectral peak where the guinea pig was tuned best (8 kHz). Thus, even though the detailed considerations regarding hazard have grown more complex and remain speculative, the spectral tuning of the ear appears to be a major determinant in the susceptibility of the ear to intense sounds.

The contention that the ear is most susceptible to impulses with their energy in the midrange has also been supported, albeit from the opposite direction, in a study by Loeb and Fletcher (1968) in which human subjects were exposed to impulses produced by sparks with peak pressures of 166 dB and varying A-durations (and as a result, varying spectral peaks). In contrast to the work done here, in their study, the spectral peaks ranged *upward* from the midrange (3 kHz). The subjects reached the criterion threshold shift (30 dB at any frequency) with exposure to only four impulses when the spectral peak was at 3 kHz. As the spectral peak *went higher, an increasing number of impulses was needed* to produce a criterion shift, e.g., 85 impulses were required when the spectral peak was at 8 kHz.

F. Energy as a measure of hazard

One of the significant findings of this study is that so little energy produced so large an effect. The current tendency in national and international standards is toward using *energy as an index of hazard for all sounds* (von Gierke, 1986), even up to very high sound levels, e.g., the French DRC for impulse noise allows unprotected exposure to peak levels of 160 dB, so long as the total A-weighted energy does not exceed that in an 8-h exposure at 85 dB (8.9 J/m^2) (Ministry of Defense, 1982b). If *energy fails to rate hazard appropriately under some conditions* (as it might at high levels), the appropriateness of an energy measure becomes a crucial issue, especially when the measure fails to be conservative enough and the true hazard is underestimated.

An examination of some of the data on energy and hearing loss suggests that there are serious obstacles to the use of an energy measure at high levels. It is recognized that results obtained from one species should be applied to another only with great caution due to potential differences in the systems (Saunders and Tilney, 1982); however, it is generally accepted that mammalian ears are similar (Dancer, 1981), and with that caveat, the energy calculations are presented.

The total energy in the exposure in the present experiment at 145 dB was only 0.6 J/m^2; yet it produced more than 45 dB of PTS at 4 kHz. This much energy is approximately equivalent to an 8-h exposure at 74 dB or down to as little as 1/2 min at 104 dB, neither of which would be likely to produce *any* PTS in a cat ear (Lindquist *et al.*, 1954; Miller *et al.*, 1963).

An alternate means of comparison would be to seek a continuous noise exposure that would produce an effect equivalent to the impulse exposure. It has been reported that cats exposed to a continuous 115-dB broadband noise (peak at 1.5 kHz) for 2 h, developed an average PTS of 38 dB

(between 0.125 and 16 kHz) (Miller *et al.*, 1963). This exposure, which produced somewhat less PTS than the primer impulses at 145 dB, contained about 2200 J/m^2, almost 3600 times as much energy as the primer impulses!

Data from the chinchilla ear are essentially equivalent. The animals exposed to impulses in the study by Hamernik *et al.* (1987) suffered about 20% outer hair cell loss with an exposure of 1.0 J/m^2, when the sound pressures were above 130 dB. In contrast, Ward *et al.* (1983) reported that for the chinchilla ear exposed continuously to a band of noise (700–2800 Hz) at pressures below 120 dB, it would take more than $10\,000 \text{ J/m}^2$ to produce the same loss of outer hair cells.

Clearly, data from both the cat and chinchilla indicate that energy does very poorly in rating hazard across these two pressure regimes. At high levels, some metric other than energy will be needed to adequately represent hazard.

[1] In conducting the research described, the investigators adhered to the Guide for Laboratory Animal Facilities and Care as established by the Committee on the Guide for Laboratory Animal Resources, National Academy of Sciences, National Research Council.

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